

Austenite Decomposition and the Changes in Magnetic Properties

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AUSTENITE DECOMPOSITION AND THE CHANGES IN MAGNETIC PROPERTIES*

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Abstract

This paper presents a part of the experimental results obtained in a study of a 5-per cent tungsten magnet steel. The investigation had for its purpose the determination of a possible relationship between the magnetic properties and the austenite retained under different quenching conditions. Two methods of decomposing the retained austenite have been used, tempering and immersion in liquid air.

WHILE austenite, the stable form of the iron-carbon alloys above the critical temperature, is nonmagnetic in character, it has been suggested that possibly there is a critical amount of austenite, which for each composition of magnet steel yields a maximum permanence. If so, then it would be expected that the decomposition of austenite retained by rapid cooling was in some way related to the change in magnetic properties. Varying proportions of austenite may be retained at room temperature by the use of suitable quenching media when the quenching takes place from favorable temperatures. The austenite retained in the quenched condition may then be made to decompose during tempering at successively higher temperatures or during immersion in liquid air. It was the purpose of this investigation to study the effect of austenite decomposition in a five per cent tungsten steel on the change in magnetic properties. A relationship between the decomposition of austenite and the change in magnetic properties was anticipated.

Since it is well known that changes in the density and hardness of quenched steels occur during tempering, it was believed that by observing the changes in density and the changes in Rockwell C

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hardness that the range of temperature wherein austenite decomposition is most pronounced might be determined. Knowing the range of tempering temperature most favorable to austenite decomposition, then the changes in magnetic properties which occur within this temperature range could also be determined.

Using liquid air immersion as a means of decomposing the retained austenite, the change in density and changes in magnetic properties were also studied. Similarly by observing the changes in density of the quenched steel when subjected to immersion treatment in liquid air, it was possible to obtain the relationship between retained austenite and the change in magnetic properties.

REVIEW OF THE LITERATURE

During the past fifteen years, interest in the subject of retained austenite has steadily grown and many papers have been published relating to the preservation of austenite in quenched steels, and to its subsequent decomposition. In reviewing the work of previous investigators a brief outline of the conclusions pertaining to austenite is given. This is followed with a more detailed account of the work of a few investigators. The conclusions are outlined briefly as follows:

1. Austenite is shown by the method of X-ray spectrum analysis to be solid solution of carbon or iron-carbide in gamma iron.
2. Austenite is always present with martensite in medium or high carbon steels quenched from the normal hardening temperatures.
3. Higher quenching temperatures in general favor the retention of greater proportion of austenite.
4. The presence of certain alloying elements favors the retention of austenite at room temperatures in quenched steels.
5. Quenching in oil retains a larger proportion of austenite than either water or 5 per cent sodium hydroxide quenches.
6. Gamma iron and austenite are nonmagnetic in character.
7. Retained austenite shows a marked difference in stability upon immersing the quenched steels in liquid air. In the case of carbon steels liquid air immersion causes practically complete decomposition of retained austenite. In alloy steels no definite statement applies.
8. Austenite decomposition in liquid air causes an increase in hardness, expansion in volume, and the formation of martensite.
9. Austenite decomposition by tempering usually produces troostite.
10. When austenite is made to decompose on tempering, the temperature range most favorable for decomposition is dependent on the alloying elements present and their concentration. Time of heating at temperature plays an

important part in the decomposition of austenite during tempering. A long time at a low temperature will cause the same effect as a shorter time at a higher temperature.

11. In the tempering of quenched carbon steels, there are two processes which take place: first, the decomposition of martensite taking place over a wide range of temperature, beginning at a tempering temperature of 212 degrees Fahr. (100 degrees Cent.) and continuing until 752 degrees Fahr. (400 degrees Cent.) is reached; and second, the decomposition of austenite which takes place over a shorter interval of temperature, starting at approximately 302 degrees Fahr. (150 degrees Cent.) and ending before a tempering temperature of 572 degrees Fahr. (300 degrees Cent.) is reached.

12. Austenite retained in quenched steels is rendered less stable by deformation.

13. The hardness of the various metallographic constituents of hardened and tempered steel varies in order of decreasing hardness as follows: martensite, troostite, austenite, sorbite, pearlite, ferrite.

14. The density of the various constituents of steel are given in order of decreasing density, or increasing volume: carbides, austenite, ferrite plus carbide, and martensite.

The reader is referred to the work of Dowdell and Harder (1) for a more detailed account of previous investigations relating to retained austenite and its decomposition.

Nusbaum (2) showed the effect of tempering on the magnetic properties of a 1.04 per cent carbon steel quenched in oil and in water from 1472 degrees Fahr., (800 degrees Cent.). In tempering between 392 degrees Fahr. (200 degrees Cent.) and 572 degrees Fahr. (300 degrees Cent.) he obtained a decrease in hardness and coercive force H_c accompanied by an increase in maximum reduction B_m , and residual induction B_r .

Mathews (3) showed the effect of liquid air immersion on the magnetic properties of a 5 per cent tungsten steel containing 0.74 per cent carbon. Upon liquid air immersion of the quenched steel, he observed an increase in the maximum induction B_m , residual induction B_r , quotient B_r/H_c , and Rockwell C hardness, and a decrease in the coercive force H_c . He points out the possible value of the quotient B_r/H_c as a criterion for the quality of permanent magnets in preference to the product $B_r \times H_c$ when comparing the results of different laboratories.

Dowdell and Harder (4) conducted liquid oxygen experiments on a number of austenitic steels. They conclude that the "austenitic structure produced in quenched steels have different stabilities and

that they show different amounts of decomposition when subjected to the liquid oxygen immersion. In the plain carbon steels, the decomposition goes practically to completion, while in the case of manganese and high speed steel there is little or no decomposition." They state that austenite decomposition in liquid oxygen appears to be a recrystallization phenomenon which shows itself first along the slip planes.

Bain and Waring (5) conducted liquid air immersion experiments on two steels: an oil hardening die steel containing 0.82 per cent carbon and 1.65 per cent manganese, and a stainless steel containing 0.30 per cent carbon and 12.78 per cent chromium. They concluded "that whatever changes are brought about by extremely low temperatures are not caused by a steep thermal gradient within the metal and the accompanying stresses. The uniform low temperature is apparently sufficient to destroy the austenite and further liquid air treatment accomplishes little or nothing. The increase in permeability and expansion indicates that austenite is removed, while the hardness increase and the other magnetic changes indicate the formation of martensite." The results of Bain and Waring show the effect of liquid air immersion upon the magnetic properties of the oil hardening die steel. They obtain an increase in hardness, an increase in length, an increase in maximum induction, an increase in residual inductance, and an increase in coercive force.

Honda (6) concludes that the effect described by Mathews, i. e., that more austenite is retained by oil quenching than in water quenching, is valid only for thick plates and rods. For thickness less than $2\frac{3}{4}$ millimeters Honda finds more austenite in the water-quenched specimens than in the oil-quenched specimens. When the thickness is greater than $2\frac{3}{4}$ millimeters, more austenite is retained by oil quenching. His experiments were concluded with a 2.96 per cent chromium steel containing 0.84 per cent carbon. Upon immersion of the quenched plates in liquid air the amount of transformation is less, the thicker the specimens.

Upon quenching from a high temperature into water, a series of carbon steels, varying in carbon content, Honda and Osawa (7) showed that more austenite was retained in the section nearer the surface than on the inner layer. This was affirmed by the relative intensity of the spectral lines, by microscopical examination, and by the distribution of hardness.

Tammann and Scheil (8) and Schroeter (9) conclude that the austenite to martensite reaction during immersion in liquid air actually takes place at the low temperature and not upon reheating to room temperature.

In a recent paper Mäurer and Schroeter (10) estimated the austenite content of eight different quenched steels by means of the values of magnetic induction at the point of saturation. The percentage difference in magnetic induction of the steel in the quenched and annealed conditions was used as a criterion for the amount of austenite present. The following results were given for a steel containing 0.73 per cent carbon, 5.51 per cent tungsten, 0.41 per cent chromium and 0.18 per cent manganese.

Quenching Temperature		Quenching Medium	Austenite As Quenched	Immersion in Liquid Air
Degrees Fahr.	Degrees Cent.			
(1472)	800	oil	10.0	8.5
(1652)	900	oil	13.0	9.5
(1832)	1000	oil	12.5	9.5
(2012)	1100	oil	11.5	8.0
(2192)	1200	oil	11.5	7.0
(1472)	800	water	6.5	6.0
(1652)	900	water	8.5	7.5
(1832)	1000	water	8.5	8.0
(2012)	1100	water	8.5	7.0
(2192)	1200	water	8.0	...

EXPERIMENTAL PROCEDURE

The experimental procedure falls naturally into three parts: first, choice of a material; second, procedure in heat treatment; and third, procedure in collecting experimental results.

Choice of a Material. The steel used for this investigation of the effect of the decomposition of retained austenite on magnetic properties was a tungsten magnet steel. The composition is given by the following chemical analysis:

	Per Cent
Carbon	0.60
Tungsten	5.70
Manganese	0.27
Vanadium	0.11
Chromium	0.36
Sulphur	0.007
Silicon	0.23
Phosphorous	0.014

This steel was used in preference to several other steels on account of the fact that it gave, in a few preliminary experiments, the greatest change in density upon quenching in comparison with the other steels available at the time this investigation was started. It was thought that the greater change in density upon quenching indicated more austenite retained at room temperature.

The steel was furnished in three-eighth inch round bars approximately thirty inches long. Bars to be used in magnetic determinations were cut to a length of ten inches, while the bars to be used in density and hardness measurements were cut into five-inch lengths. The five-inch bars weighed approximately sixty-five grams in air.

Heat-Treatment. Previous to the quenching treatment the various sets of bars were given a preliminary heat treatment by heating for a period of six hours at 1600 degrees Fahr. (871 degrees Cent.), followed by cooling in air. The normalizing treatment was carried out by suspending the bars in an electric tube furnace.

In order to have a convenient datum plane on which to base the changes in properties of the magnet steel, it was decided to use the properties existing after annealing for a period of four hours at 1750 degrees Fahr. (955 degrees Cent.) followed by slow cooling in the furnace. Three ten-inch bars and three five-inch bars were suspended in the same furnace used in normalizing.

In conducting the quenching treatments a standard practice was adhered to in order to eliminate as many variables as possible. The five-inch bars for density determinations and the ten-inch bars for magnetic measurements were quenched simultaneously. The bars were placed in the cold furnace, heated with the furnace to the quenching temperature, held for the predetermined time and quenched. Before the bars reached the temperature of the quenching medium, they were removed and placed in boiling water, where they were held for a period of one and one-half hours. This procedure was previously found to prevent quenching cracks at the higher quenching temperatures. In quenching the bars the descent into the quenching medium was made vertically and as rapidly as possible. The details of the quenching treatments are given in Table I. The time of soaking at the quenching temperature was made long in order to give the carbides and tungstides ample time to go into solution. Owing to the two hour heating period at the quenching temperature, the outer surfaces of the bars suffered some decarburization. The extent of this decarburization was checked by metallographic examination and was found not to exceed one one-hundredth of an inch in the bars quenched from 1900 degrees Fahr. (1038 degrees Cent.).

In a like manner the tempering treatments were carried out in accordance with a definite plan. The time at temperature was 120

minutes excepting at a temperature of 212 degrees Fahr. (100 degrees Cent.), where the time of tempering was twelve and one-half hours. The bars were tempered at 212 degrees Fahr. (100 degrees Cent.) in water, at 392 degrees Fahr. (200 degrees Cent.) and 572 degrees Fahr. (300 degrees Cent.) in oil, and at the higher temperatures in

Table I
Quenching Treatments

Quenching Temperature	Quenching Medium	Temperature of Quenching Medium	Time at Quenching Temperature in Minutes	Type of Heating
1600° F (871° C)	Oil	22° C	120	Electric tube furnace with charcoal.
	Water	21° C	120	
	5% NaOH	20° C	120	
1700° F (933° C)	Oil	20° C	120	Electric tube furnace with charcoal.
	Water	22° C	120	
	5% NaOH	23° C	120	
1800° F (983° C)	Oil	27° C	120	Electric tube furnace with charcoal.
	Water	32° C	120	
	5% NaOH	37° C	120	
1900° F (1038° C)	Oil	23° C	120	Gas fired muffle furnace with charcoal.
	Water	23° C	120	
	5% NaOH	19° C	120	
2000° F (1097° C)	Oil	26° C	90	Gas fired muffle furnace with charcoal.
	Water	26° C	90	
	5% NaOH	24° C	90	

an electric tube furnace. The bars to be tempered were placed in the cold furnace, heated to the desired temperatures, held for 120 minutes, removed from the furnace and allowed to cool in air. Successive tempering operations at higher temperatures were performed on the same set of bars.

Immersion treatment in liquid air was carried out in four periods: 8 hours, 52 hours, 58 hours, and 57 hours, making the total time of immersion equal to 175 hours. The bars were placed in a Dewar tube about 13 inches deep; liquid air was then poured carefully over the bars a little at a time in order not to cause excessive boiling. Additions of liquid air were made frequently to maintain the level above the ends of the bars. During the last 12 hours of the longer runs, no additional air was added and the liquid allowed to evaporate, although in no instance was it completely evaporated at the time of removing the bars from the tube.

Methods of Collecting Results. Density determinations, magnetic measurements, and Rockwell C hardness values were made on the tungsten steel bars for the various conditions of heat treatment

and periods of immersion in liquid air. The methods used in making these measurements will be discussed briefly in the following paragraphs.

The tungsten steel bars used in the determination of the density were carefully prepared by polishing with coarse and fine emery paper, followed by washing thoroughly in alcohol and ether. After washing, the bars were handled with a small piece of chamois skin in order to prevent corrosion from the moisture of the hands.

The density was determined by the Archimedean principle. The procedure was the same as that described by Norbury (11), in which special precautions were outlined to eliminate as far as possible the errors arising from surface tension.

The magnetic properties were determined with a direct current Fahy Simplex Permeameter. The values of residual inductance and coercive force were obtained by plotting the hysteresis curves for the several conditions of heat treatment and immersion treatments in liquid air.

The Rockwell C hardness values were taken with a diamond point penetrator under a total load of 160 kilograms. Specimens used in hardness measurements, having a length of approximately three-eighths of an inch, were cut from the ends of the density bars after each treatment. The specimens were prepared by polishing both ends of the small cylinders with number zero (No. 0) emery paper, insuring a uniform surface condition of all specimens. The average of five readings was taken as the hardness of the specimen.

EXPERIMENTAL RESULTS

The discussion of the results obtained conveniently divides itself into two parts: first, the discussion of results obtained when the austenite is decomposed upon tempering; and second, the discussion of results obtained when the austenite is decomposed during immersion in liquid air.

Results of Tempering Experiments. Since the variation in density and hardness of quenched steels during tempering treatments are fairly well known, it was thought, by observing the changes in slope of the curves representing the change in density and the change in hardness, that the range of temperature most favorable to the decomposition of austenite might be determined. Knowing this temperature range, it would then be possible to determine from the curves representing the changes in the magnetic properties which occur upon

tempering, those changes which may be attributed to the decomposition of austenite. The data for the curves representing the changes in properties of the tungsten steel upon tempering at successively higher temperatures were calculated, using as a basis the values obtained in the annealed condition. The basic values are given in Table II for an anneal of four hours at 1750 degrees Fahr. (955 degrees Cent.).

Change in Density. In every instance, referring to Table II, the density of the oil-quenched specimens was greater than the density of the bars quenched in water or 5 per cent sodium hydroxide. This indicates a greater retention of austenite in the bars quenched in oil, which is in agreement with the view of Mathews and others. A greater retention of austenite in the bars quenched from the higher temperature is indicated by the greater change in density during the quenching treatment. In considering the water and 5 per cent sodium hydroxide quenching treatment no definite statement covers all instances. When the quenching temperature was 1800 degrees Fahr. (983 degrees Cent.) or above, the specimens quenched in water showed a greater density than those quenched in 5 per cent sodium hydroxide. On the other hand, when the quenching was carried out below 1800 degrees Fahr. the density of the bars quenched in 5 per cent sodium hydroxide gave the greater density.

The curves representing change in density with tempering temperature for the bars quenched from 2000 degrees Fahr. (1097 degrees Cent.) are shown in Fig. 1. Three distinct changes in the slope of the curves were found common for all quenching temperatures: first, at 572 degrees Fahr. (300 degrees Cent.); second, at 977 degrees Fahr. (525 degrees Cent.); and third, at 1121 degrees Fahr. (605 degrees Cent.). These changes in slope of the curves representing changes in density with tempering temperature may be attributed to the separate or combined influence of the following factors.

1. Release of quenching stress and distortion of the space lattice, resulting in an expansion in volume or a decrease in density.
2. Precipitation and coalescence of carbide particles resulting in a contraction in volume or an increase in density.
3. Decomposition of martensite causing a contraction in volume or an increase in density.
4. Decomposition of austenite causing an expansion in volume or a decrease in density.

In addition to the three common changes in slope for all quench-

Table II
Tabulated Experimental Findings

Quenching Temperature	Quenching Medium	Quench Condition, $H_{max} = 200$ Gilberts/cm				Density of Liquid Air Bar for Immersion	Mean Density of Two Bars for Drawing Experiments	Rockwell "C" Hardness
		Bm	Gauss	Gil/cm	Br $\times$ Hc	Br/Hc		
1600° F (871° C)	Oil	12790	7970	47.1	375,000	169	8.0787	64
	Water	14090	9410	47.0	442,000	200	8.0647	63
	NaOH	14180	9340	46.8	437,000	199	8.0652	62
		13730	7930	44.3	351,000	179	8.0775	62
1700° F (933° C)	Oil	14380	9320	44.5	415,000	209	8.0680	62
	Water	14420	8800	44.5	391,500	198	8.0681	62
1800° F (983° C)	Oil	12220	7420	47.1	349,000	158	8.0761	62
	Water	12800	7970	45.1	359,000	177	8.0695	63
	NaOH	13410	8280	43.3	359,000	191	8.0667	62
1900° F (1038° C)	Oil	13300	8200	49.1	402,500	167	8.0706	62
	Water	13850	9040	45.5	411,000	199	8.0647	63
	NaOH	14300	9350	43.6	407,500	214	8.0614	63
2000° F (1097° C)	Oil	13050	7700	44.5	342,700	173	8.0660	62
	Water	13890	8280	39.8	329,500	208	8.0634	63
	NaOH	13650	8490	41.9	355,700	203	8.0601	64
Normalized at 1600° F (871° C) for 6 hours.		15540	9060	24.1	218,500	376	8.0933	36
Annealed at 1750° F (954° C) for 4 hours.		16540	11650	10.7	124,700	1089	8.0977	26

ing temperatures, the curves for the bars quenched from 2000 degrees Fahr. (1097 degrees Cent.) show a slight decrease in density upon tempering between 392 degrees Fahr. (200 degrees Cent.) and 572 degrees Fahr. (300 degrees Cent.). A similar effect was observed for the oil-quenched bars only, when the quenching temperature was

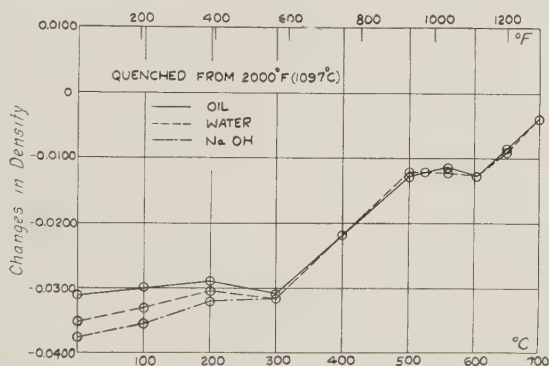


Fig. 1—Change in Density upon Tempering. Values Obtained in Annealed Condition Were Used as a Basis.

1900 degrees Fahr. (1038 degrees Cent.) and below. The amount of decrease was greater at the lower quenching temperature of 1600 degrees Fahr. (871 degrees Cent.). This effect is believed to be a result of a partial decomposition of austenite, fourth factor, upon the tempering of the oil-quenched specimens.

The increase in density which occurs upon tempering up to 392 degrees Fahr. (200 degrees Cent.) in the water-quenched bars and in 5 per cent sodium hydroxide quenched bars is probably a result of the predominant influence of the second factor, precipitation and coalescence of cementite particles. This conclusion is indicated by the relative increase in density between the oil, water and 5 per cent sodium hydroxide quenched specimens. The increase in density is least for oil where precipitation during quenching takes place over a longer period and greater where precipitation is retarded by more rapid quenching.

From Fig. 1 it is observed the differences in density between oil, water and 5 per cent sodium hydroxide quenched specimens disappear when the tempering temperature reaches 572 degrees Fahr. (300 degrees Cent.). This is believed to be a result of relieving differences which arose during the quenching treatment; namely, differences in stability and amount of retained austenite, differences

in quenching stress and differences in amount of ferrite and cementite particles.

In tempering above 572 degrees Fahr. (300 degrees Cent.) the change in density is a uniform increase showing the predominance of the third factor, resulting in a uniform growth of ferrite particles and martensite decomposition, until a temperature of 977 degrees Fahr. (525 degrees Cent.) is reached. Additional evidence of the influence of martensite decomposition is indicated by the nearly constant value of the slope of the curves representing the changes in density for the five quenching temperatures, which are given as follows:

Quenching Temperature Degrees Fahr. Degrees Cent,		Slope of Density Curve for Centigrade Temperature
1600	(871)	7.7×10^{-5}
1700	(932)	7.9×10^{-5}
1800	(981)	7.9×10^{-5}
1900	(1038)	8.7×10^{-5}
2000	(1097)	9.1×10^{-5}

In tempering the bars quenched from 2000 degrees Fahr. (1097 degrees Cent.) between 977 degrees Fahr. (525 degrees Cent.) and 1121 degrees Fahr. (605 degrees Cent.) the density remains practically constant. This evidence points to the conclusion that the retained austenite decomposes during tempering within this temperature range and that the decomposition of martensite and austenite, factors three and four, proceed at rates which counterbalance each other as indicated by the small net change in density over this range of temperature. In tempering above 1121 degrees Fahr. (605 degrees Cent.) the slope of the curves which represent the change in density with tempering temperature, is approximately the same as the slope below 977 degrees Fahr. (525 degrees Cent.). This supports the view that martensite is a product of the decomposition of austenite during tempering and that the changes occurring in the magnet steel upon tempering are the same immediately above the range of temperature most favorable to the decomposition of austenite as immediately below that range.

Change in Rockwell C Hardness. The curves representing the change in hardness with tempering temperature are shown graphically in Fig. 2 for the specimens quenched from 2000 degrees Fahr. (1097 degrees Cent.). The changes in hardness during tempering of the quenched tungsten magnet steel give added confirmation to the conclusions already drawn from the density experiments. Practically full hardness was developed in the tungsten steel during quenching.

which is in agreement with the work of Mathews (3). The curves showing the change in hardness during tempering of the oil, water, and 5 per cent sodium hydroxide quenched bars fall close together over the whole range of tempering temperature. Little difference in hardness was observed in the three quenching mediums. The slope

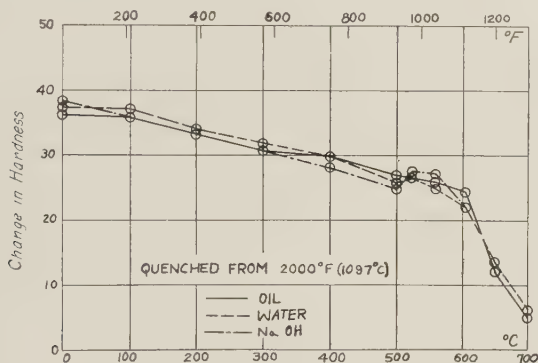


Fig. 2—Change in Rockwell C Hardness upon Tempering. Values Obtained in Annealed Condition Were Used as a Basis.

of the change in hardness curves is practically a constant between 212 degrees Fahr. (100 degrees Cent.) and 932 degrees Fahr. (500 degrees Cent.) as shown by the following table:

Quenching Temperature Degrees Fahr.	Quenching Temperature Degrees Cent.	Slope of Hardness Curve
1600	(871)	-3.3×10^{-2}
1700	(932)	-3.2×10^{-2}
1800	(983)	-3.0×10^{-2}
1900	(1038)	-2.7×10^{-2}
2000	(1097)	-2.7×10^{-2}

The constant slope of the change in hardness curves indicates that retained austenite is preserved during tempering until a temperature of 977 degrees Fahr. (525 degrees Cent.) is reached. The change in hardness curves for the lower quenching temperatures fall off more quickly with tempering temperature than those for the higher quenching temperatures upon increasing the temperature above 932 degrees Fahr. (500 degrees Cent.). In the bars quenched from 1900 degrees Fahr. (1038 degrees Cent.), and 2000 degrees Fahr. (1097 degrees Cent.) the phenomenon of secondary hardness, described by Bain (12), was noticeable. This points to a greater retention of austenite in the specimens quenched from the higher temperatures. The fact that retained austenite decomposes most readily during tempering

above 977 degrees Fahr. (525 degrees Cent.) is indicated by the secondary hardness effect, which substantiates the conclusions obtained from the changes in density, page 740.

Change in Magnetic Properties. Since the range of temperature most favorable to austenite decomposition during tempering has been located, it now remains to observe the change in magnetic properties which occur upon tempering within this range. The data for the curves representing the changes in magnetic properties were calculated from the values of maximum induction Bm, residual induction Br, and coercive force Hc, using as a basis the values of these properties obtained after an anneal of four hours at 1750 degrees Fahr. (955 degrees Cent.).

In Fig. 3 the curve representing the change in maximum induction Bm with tempering temperature is given for the specimens quenched from 2000 degrees Fahr. (1097 degrees Cent.). The maximum induction Bm, increases with tempering until a temperature of 572 degrees Fahr. (300 degrees Cent.) is reached. The value of Bm, remains approximately constant between 572 degrees Fahr. and 932 degrees Fahr. (500 degrees Cent.) for all quenching temperatures, 1600 degrees Fahr. (871 degrees Cent.) to 2000 degrees Fahr. (1097 degrees Cent.) inclusive. In tempering above 932 degrees Fahr. (500 degrees Cent.) Bm is observed to fall off, beginning as follows, for the different quenching temperatures:

Quenching Temperature		Bm Begins to Decrease Upon Tempering at	
Degrees Fahr.	Degrees Cent.	Degrees Cent.	Degrees Fahr.
1600	(871)	500	(932)
1700	(933)	500	(932)
1800	(983)	525	(977)
1900	(1038)	560	(1040)
2000	(1097)	605	(1121)

It is seen from the table that the maximum value of B max. is maintained over a longer range of tempering temperatures in the specimens quenched from the higher temperatures. This is analogous to the retention of hardness at higher temperatures in the specimens quenched from 2000 degrees Fahr. (1097 degrees Cent.), see page 741. The value of Bm is observed to fall off with the decomposition of retained austenite during tempering. Noticeable differences in maximum induction caused by quenching in different mediums, oil, water and 5 per cent sodium hydroxide, become less as the tempering temperature increases. Oil quenching was found to produce the lower value of Bm for each quenching temperature.

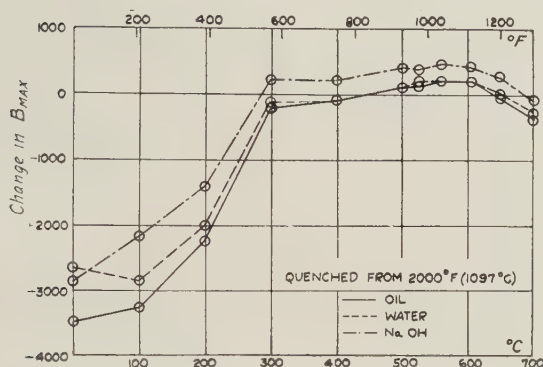


Fig. 3—Change in Maximum Induction Upon Tempering. Values Obtained in Annealed Condition Were Used as a Basis.

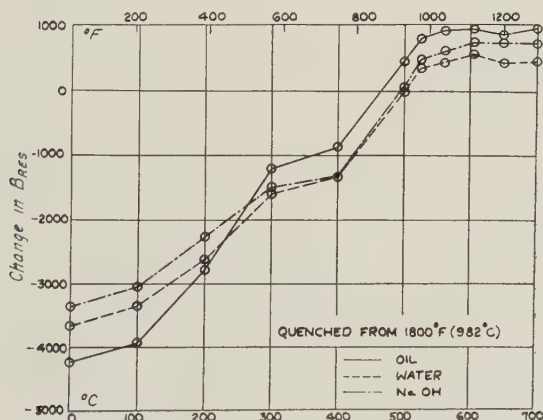


Fig. 4—Change in Residual Induction Upon Tempering. Values Obtained in Annealed Condition Were Used as a Basis.

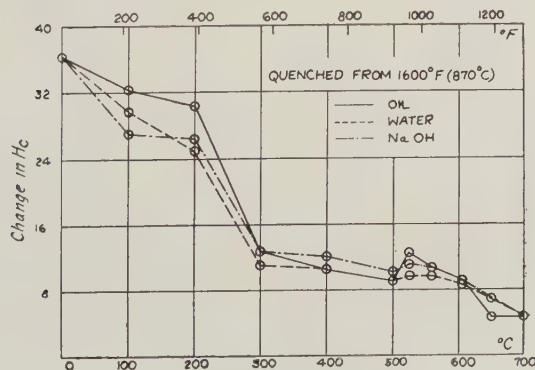


Fig. 5—Change in Coercive Force Upon Tempering. Values Obtained in Annealed Condition Were Used as a Basis.

In Fig. 4 the changes in residual induction are represented graphically for the specimens quenched from 1800 degrees Fahr. (983 degrees Cent.). From the curves it would appear that a very definite maximum in Br occurs upon tempering at 977 degrees Fahr. (525 degrees Cent.); or, in other words, austenite decomposition is accompanied by an increase in the value of the residual induction. Oil-quenched specimens in every instance gave the lower value of Br.

The change in coercive force, Hc, upon tempering is plotted in Fig. 5 for the specimens quenched from 1600 degrees Fahr. (871 degrees Cent.). The value of Hc decreases with tempering up to a temperature of 572 degrees Fahr. (300 degrees Cent.). The coercive force remains approximately constant from this point until the temperature reaches 932 degrees Fahr. (500 degrees Cent.). An increase in the value of Hc occurs for all quenching temperatures upon tempering at 977 degrees Fahr. (525 degrees Cent.). This change in the coercive force has the same direction as the change which is found to occur in the quenching treatment and indicates the formation of martensite as a result of austenite decomposition during tempering.

The change in the product $Br \times Hc$, occurring upon tempering the quenched 5 per cent tungsten steel at successively higher temperatures, is shown in Fig. 6 for the bars quenched from 1800 degrees Fahr. (983 degrees Cent.). Upon tempering, the product $Br \times Hc$ shows an increase beginning at 977 degrees Fahr. (525 degrees Cent.) for all quenching temperatures.

The differences between the $Br \times Hc$ values for oil and water quenches and for oil and five per cent sodium hydroxide quenches are plotted in Fig. 7 with the quenching temperatures. It is clearly shown that a relationship exists, at least up to a quenching temperature of 1900 degrees Fahr. (1038 degrees Cent.), even though this may not be expressed mathematically.

Inspection of Fig. 7 shows that a very large difference in the $Br \times Hc$ values for oil and water quenches was obtained between the quenching temperatures, 1700 degrees Fahr. (933 degrees Cent.) and 1800 degrees Fahr. (983 degrees Cent.). Immediately above and immediately below, however, the difference in $Br \times Hc$ values for oil and water quenches tends to be a constant. The difference in $Br \times Hc$ value for the oil and water quenches shows a step decrease with quenching temperature.

The first change in the quotient Br/Hc during tempering is an increase, which becomes most marked in tempering between 392 degrees Fahr. (200 degrees Cent.) and 572 degrees Fahr. (300 degrees Cent.). Upon tempering at 977 degrees Fahr. (525 degrees Cent.) a marked decrease in Br/Hc occurs, as shown in Fig. 8 for the specimens quenched from 1600 degrees Fahr. (871 degrees Cent.). This

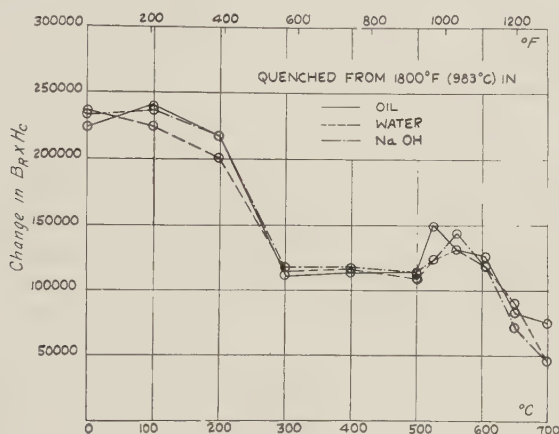


Fig. 6—Change in Product $Br \times Hc$ Upon Tempering. Values Obtained in Annealed Condition Were Used as a Basis.

effect is most pronounced in the bars quenched from the lower temperatures. The value of Br/Hc for the oil quench is less than the value for the water or 5 per cent sodium hydroxide quenches up through a tempering temperature of 572 degrees Fahr. (300 degrees Cent.). Austenite decomposition during tempering is accompanied by a decrease in Br/Hc . This change has the same direction as the change in Br/Hc which occurred upon quenching.

In the quenched condition the difference in the value of Br/Hc between oil and water, and oil and 5 per cent sodium hydroxide quenched specimens shows a definite tendency to become a constant, the average value of which is 29 and 32, respectively. This relationship is brought out in the following table:

Quenching Temperature	1600° Fahr. (871° Cent.)	1700° Fahr. (933° Cent.)	1800° Fahr. (983° Cent.)	1900° Fahr. (1038° Cent.)	2000° Fahr. (1097° Cent.)	Average Value
Value of Br/Hc for oil	169	179	158	167	173	169
Value of Br/Hc for water	200	209	177	199	208	197
Difference	31	30	19	32	35	29
Value of Br/Hc for oil	169	179	158	167	173	171
Value of Br/Hc for 5% NaOH	199	198	191	214	203	201
Difference	30	19	33	47	30	32

It is believed that the water and NaOH quenches while differing from each other are sufficiently rapid in comparison with oil quenching that they lie on the same side of a critical rate of cooling which causes the nearly constant difference in Br/Hc values of oil and water, and oil and NaOH quenched specimens. Not only does

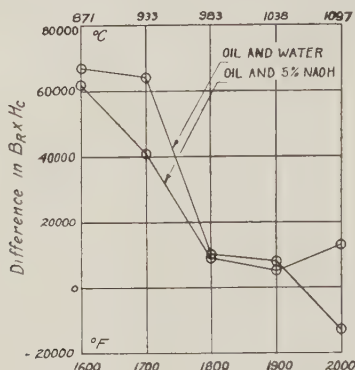


Fig. 7—Shows Difference in Product $B_R \times H_c$ for Oil and Water, and Oil and 5 Per Cent NaOH Quenches for Different Quenching Temperatures.

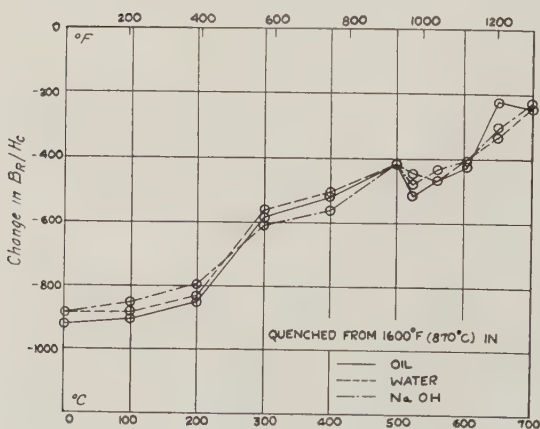


Fig. 8—Change in Quotient B_R/H_c Upon Tempering. Values Obtained in Annealed Condition Were Used as a Basis.

the difference in the values of the quotient B_R/H_c for oil and water, and oil and sodium hydroxide tend to become a constant; but also, the value of the quotient B_R/H_c itself shows a definite tendency to become a constant independent of the quenching temperature.

If the maximum point on the permeability curve, which occurs between a magnetizing force of 15 and 70 Gilberts per centimeter, is plotted against the tempering temperature, the curves in Fig. 9 for oil-quenched bars are obtained. The permeability B/H was calculated from the normal induction data. From this figure it will be

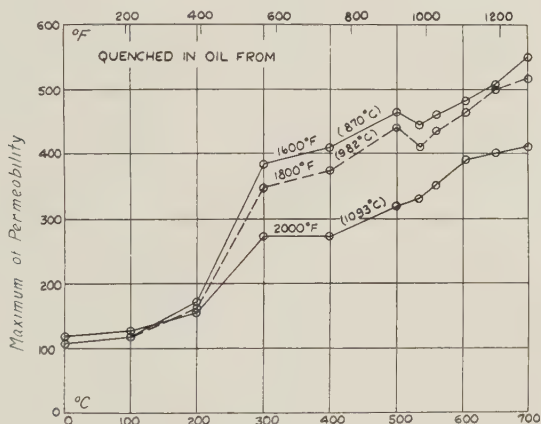


Fig. 9—Showing Maximum of Permeability with Tempering Temperature.

observed that a break in the maximum of permeability occurs upon tempering above 977 degrees Fahr. (525 degrees Cent.). This break is most pronounced, first, when the quenching is carried out at 1600 degrees Fahr. (871 degrees Cent.); and, second, when the quenching is carried out in oil.

Results of Liquid Air Experiments

The effect of the decomposition of retained austenite during immersion in liquid air upon the magnetic and other properties was studied by determining the change in density, the change in Rockwell C hardness and the changes in the magnetic properties with time of immersion in liquid air. The changes in properties during immersion in liquid air were calculated from the values observed, using as a basis the values obtained in the quenched condition for the graphical representation of the changes.

The changes in density upon immersion in liquid air are shown graphically in Figs. 10 and 11. The differences in behavior of the water and 5 per cent sodium hydroxide quenched specimens, which existed in the quenched condition, see page 739, were found to hold

throughout the treatments in liquid air. This indicates that the differences in behavior observed were dependent upon variables controlled by the quenching treatment.

It was shown previously that the greater change in density during quenching took place in the specimens quenched from 2000

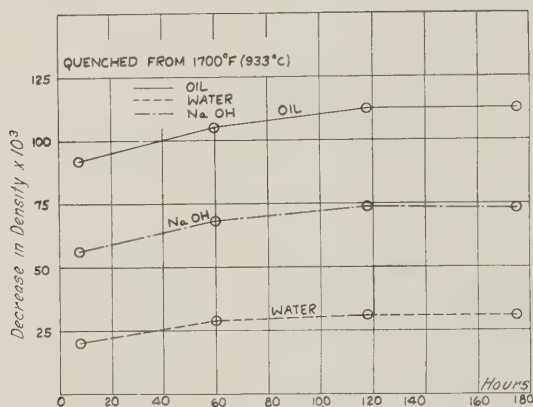


Fig. 10—Change in Density During Liquid Air Immersion. Values Obtained in Quenched Condition Were Used as a Basis.

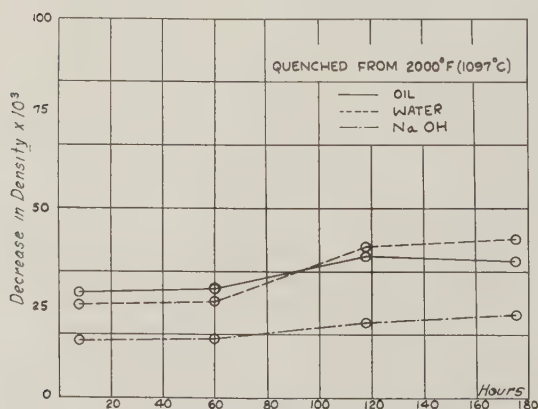


Fig. 11—Change in Density During Liquid Air Immersion. Values Obtained in Quenched Condition Were Used as a Basis.

degrees Fahr. (1097 degrees Cent.). On the other hand, when the quenched tungsten steel bars were given an immersion treatment in liquid air, the greater change in density took place in the bars quenched from 1600 degrees Fahr. (871 degrees Cent.). This dif-

ference in behavior of the bars quenched at the lower and higher quenching temperatures is indicative of the relative stability of austenite retained under these conditions. It is, therefore, indicated that quenching from the higher temperature results in a greater degree of stability for austenite which is subjected to immersion in liquid air.

The change in density in no instance was complete after eight hours immersion in liquid air, although the greater proportion of the total change occurred during the first eight hour immersion, as shown in the following table.

Quenching Temperature		Quenching Medium	Per cent of total change in density for 175 hour total immersion which occurs in first eight hour immersion.
Degrees Fahr.	Degrees Cent.		
1700	(933)	Oil	82
		Water	65
		5 per cent NaOH	77
2000	(1097)	Oil	71
		Water	75
		5 per cent NaOH	70

If the density change may be an indication of the progress of austenite decomposition during immersion in liquid air, then this observation is not in agreement with the work of Bain and Waring (5) in which they conclude that "the uniform low temperature is apparently sufficient to destroy the austenite and further liquid air treatment accomplishes little or nothing."¹ It is shown that immersion in liquid air is not sufficient to decompose completely the austenite retained in the 5.70 per cent tungsten magnet steel. This fact is especially true at the higher quenching temperatures, shown by comparing the results obtained on a 1700 degrees Fahr. (933 degrees Cent.) quench and those where the 2000 degrees Fahr. (1097 degrees Cent.) quench was used.

Change in Rockwell C Hardness. Rockwell C hardness values are given in Tables II and IV for the quenched specimens and the specimens immersed in liquid air for a total period of 175 hours, respectively. An inspection of the tables shows that immersion in liquid air results in a decrease in hardness in nine instances out of fourteen. This observation is not in agreement with the values given by Mathews (3) for a 5 per cent tungsten steel. Two possible explanations are offered for this deviation: first, the specimens used in making the hardness measurements after immersion in liquid air were cut from different bars; and, second, the hardness values were

¹Their initial period of immersion was between 12 and 16 hours.

Table III
Tabulated Experimental Findings

Quenching Temperature	Quenching Medium	Immersed in Liquid Air for 8 Hours				Br/Hc	Density
		Bn	Gauss	Br	Hc Gil./cm.	Br $\times$ Hc	
1600° F (871° C)	Oil	.....	.....	.....	...	.....	8.0667
	Water	.....	.....	.....	...	.....	8.0610
	NaOH	.....	.....	.....	...	.....	8.0602
1700° F (933° C)	Oil	14590		9010	48.2	434,000	8.0682
	Water	14920		8670	41.7	362,000	8.0660
	NaOH	14580		9410	44.5	419,000	8.0625
1800° F (983° C)	Oil	13300		8080	46.0	371,000	8.0684
	Water	13720		8900	44.6	397,000	8.0655
	NaOH	13940		8830	43.1	381,000	8.0624
1900° F (1038° C)	Oil	14080		8710	46.3	403,000	8.0627
	Water	14450		9520	43.9	418,000	8.0620
	NaOH	14710		9530	42.7	407,000	8.0595
2000° F (1097° C)	Oil	13720		8200	43.0	352,400	8.0621
	Water	14250		8550	41.6	356,000	8.0587
	NaOH	14430		8910	38.9	347,000	8.0578

Table IV
Tabulated Experimental Findings

Quenching Temperature	Quenching Medium	Gauss Bm	Immersed in Liquid Air for 175 Hours Hmax = 200 Gilberts/cm.				Br/Hc	Density	Rockwell "C" Hardness
			Br	Gil/cm Hc	Br × Hc				
1600° F (871° C)	Oil	.....	.....	...	.....		...	8.0643	63
	Water	.....	.....	...	.....		...	8.0585	62
	NaOH	.....	.....	...	.....		...	8.0576	62
1700° F (933° C)	Oil	14560	9200	48.5	446,000		190	8.0662	61
	Water	14840	8990	41.1	369,000		219	8.0649	61
	NaOH	14540	9350	47.1	449,000		203	8.0608	62
1800° F (983° C)	Oil	13350	8260	44.4	367,000		186	8.0670	61
	Water	13720	8980	44.1	396,000		204	8.0640	62
	NaOH	13950	8830	42.1	372,000		210	8.0608	60
1900° F (1038° C)	Oil	14080	8790	46.2	406,000		191	8.0617	63
	Water	14450	9500	44.8	426,000		212	8.0607	60
	NaOH	14680	9660	42.9	414,000		225	8.0585	63
2000° F (1097° C)	Oil	13740	8330	43.8	365,000		190	8.0605	62
	Water	14240	8650	40.3	349,000		215	8.0571	61
	NaOH	14440	8920	38.5	343,000		232	8.0568	..

taken about ten months after immersion in liquid air and aging at room temperature may have produced a difference in the steel bars which were quenched only, and those quenched, followed by a 175 hour immersion in liquid air.

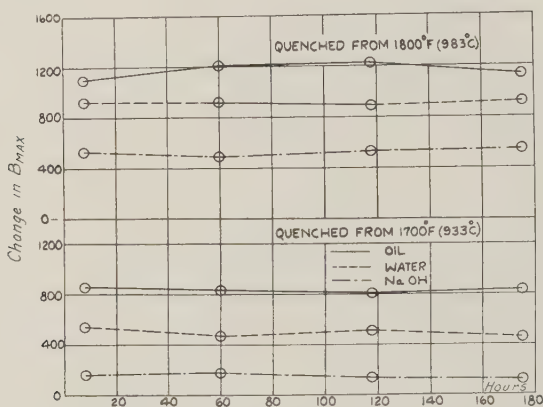


Fig. 12—Change in Maximum Induction During Liquid Air Immersion. Values Obtained in Quenched Condition Were Used as a Basis.

Change in Magnetic Properties. The changes in the magnetic properties caused by the decomposition of retained austenite in the quenched 5 per cent tungsten steel during immersion in liquid air have been observed at intervals over a total immersion of 175 hours. The properties studied consist of the changes in maximum induction (B_m), residual induction (B_r), coercive force (H_c), the product ($B_r \times H_c$), the quotient (B_r/H_c), and the permeability (B/H). The data for the curve representing the change in properties were calculated using the values obtained in the quenched condition as a basis.

The changes in B_m observed during immersion in liquid air are shown in Fig. 12 for the bars quenched from 1800 degrees Fahr. (983 degrees Cent.) and 1700 degrees Fahr. (933 degrees Cent.) for three quenching mediums: oil, water and 5 per cent sodium hydroxide. Immersion in liquid air results in an increase in the maximum induction for all quenching temperatures and for all the quenching mediums. This is in agreement with the work of Mathews, whose results are cited above. Prolonged immersion resulted in little further increase in the value of the maximum induction. On the other hand

it was shown, page 742, that the value of Bm decreased with the decomposition of austenite during tempering.

In the bars quenched at 1700 degrees Fahr. (933 degrees Cent.) to 1900 degrees Fahr. (1038 degrees Cent.), inclusive, the change in Bm upon immersion in liquid air is greater in the oil-quenched bars

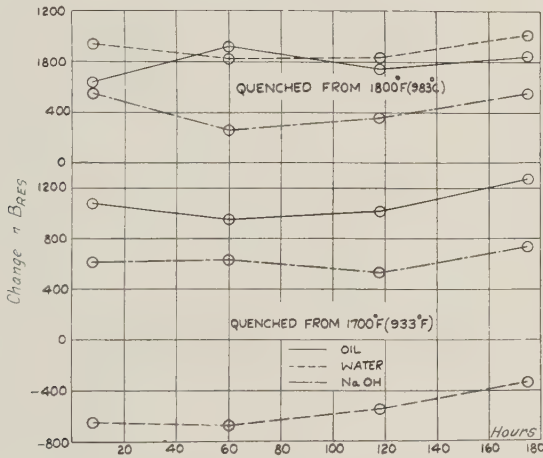


Fig. 13—Change in Residual Induction During Immersion in Liquid Air. Values for Quenched Condition Were Used as a Basis.

and less in the bars quenched in 5 per cent sodium hydroxide; while at 2000 degrees Fahr. (1097 degrees Cent.) the bars quenched in oil and 5 per cent sodium hydroxide show about the same change in Bm upon immersion in liquid air. The maximum change was produced by quenching in oil from 1800 degrees Fahr. (983 degrees Cent.), while the smallest change occurred in the bars quenched from 1700 degrees Fahr. (933 degrees Cent.) in sodium hydroxide.

The graphical representations of the change in the residual induction Br upon immersion in liquid air are given in Fig. 13 for the specimens quenched in the lower temperatures. In all instances, except the specimen quenched in water from 1700 degrees Fahr. (933 degrees Cent.), an increase in the residual induction, Br, was observed. This is in agreement with the results of Mathews previously cited and the results of Bain and Waring (5). Prolonged immersion resulted in slight further increase in the value of Br in most instances: The oil-quenched bars show the greater change in

Br upon immersion in liquid air except those quenched from 1800 degrees Fahr. (983 degrees Cent.). Similar to the change in density during immersion in liquid air, the greater change in Br occurs in the bars quenched from the lower temperatures, while the smaller

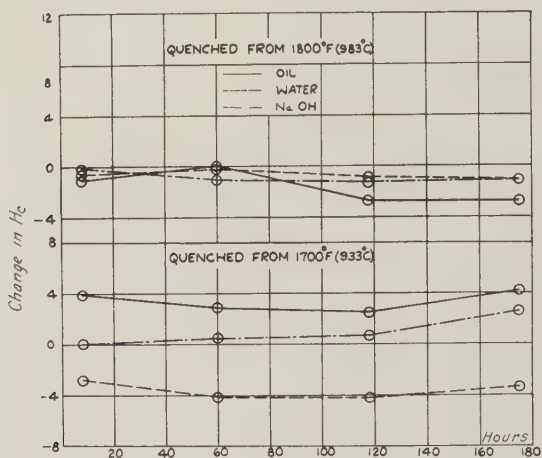


Fig. 14—Change in Coercive Force During Immersion in Liquid Air. Values for Quenched Condition Were Used as a Basis.

change in Br occurred in the specimens quenched from 2000 degrees Fahr. (1097 degrees Cent.).

In Fig. 14 are shown the changes in coercive force, produced by immersion in liquid air. In eight instances out of twelve the coercive force decreases upon immersion of the quenched bars in liquid air. This is in agreement with the results of Mathews. On the other hand, Bain and Waring (5) obtained an increase in coercive force upon immersion for a period of twelve hours; however, their results are for a low manganese steel and may not be comparable with the results just described. The decomposition of austenite during tempering was shown, page 744, to give an increase in coercive force. This striking difference in behavior is indicative of a difference in the mode of decomposition depending on whether the austenite decomposition is effected by tempering or by liquid immersion.

Immersion in liquid air gave an increase in the product $Br \times H_c$ with an exception of one instance in which the specimen was quenched in 5 per cent sodium hydroxide from 2000 degrees Fahr. (1097 de-

gress Cent.). The greater change in the product $Br \times Hc$ upon immersion in liquid air occurred with the bars quenched from the lower temperature, 1700 degrees Fahr. (933 degrees Cent.), which is similar to the change in density and to the change in residual induction.

The value of Br/Hc showed an increase after immersion in liquid air in all instances, except the specimen quenched in water from 2000 degrees Fahr. (1097 degrees Cent.). This observation is in agreement with the changes given by Mathews (3). When the period of

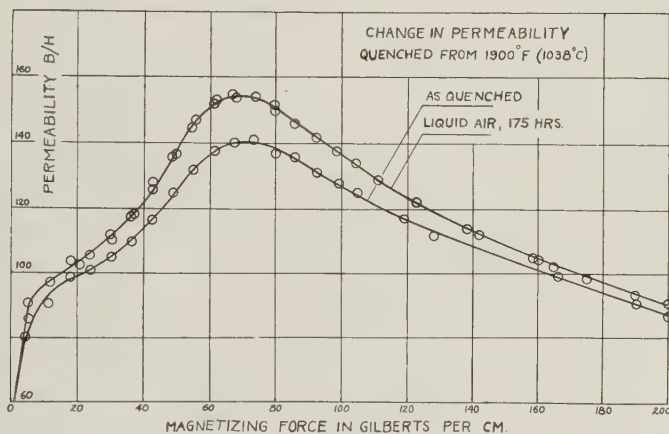


Fig. 15—Change in Permeability During Immersion in Liquid Air.

immersion exceeded sixty hours, the oil-quenched bars showed the greater change in the quotient Br/Hc except in the 2000 degree Fahr. (1097 degree Cent.) quench. The same type of relationship exists throughout the liquid air treatments, as was observed in the quenched condition between the quotient Br/Hc and quenching medium. The oil-quenched specimens show lower values of Br/Hc than either the water-quenched bars or those quenched in 5 per cent sodium hydroxide. When the quenching is carried out at 1800 degrees Fahr. (983 degrees Cent.) and above, the value of Br/Hc in the quenched condition and after liquid air treatment is lower for the oil and higher for the specimens quenched in 5 per cent sodium hydroxide.

In Fig. 15 the change in permeability B/H is given for a total of 175 hours immersion in liquid air and shows that the permeability is increased by liquid air immersion. This is directly opposite to the effect produced upon decomposing austenite by tempering at 977 degrees Fahr. (525 degrees Cent.), where a noticeable decrease in the

maximum permeability was observed. This reversal in the effect is not limited to permeability, as is evident in the following table, giving the observed changes in properties of the quenched 5 per cent tungsten steel resulting from austenite decomposition during tempering and during immersion in liquid air.

Property Observed	Change Within Tempering Temperature Range 932°F (525°C) to 1121°F (605°C)	Change Upon Immersion in Liquid Air
Density	decrease	decrease
Hardness	increase	decrease
Maximum induction B _m	decrease	increase
Residual Induction B _r	increase	increase
Coercive force H _c	increase	decrease
Product B _r x H _c	increase	increase
Quotient B _r /H _c	decrease	increase
Maximum permeability B/H	decrease	increase
Permeability B/H	decrease	increase

Austenite decomposition during tempering and upon immersion in liquid air gave opposite changes in the values of hardness, maximum induction, coercive force quotient B_r/H_c and the permeability. These differences in the effect of austenite decomposition on the properties, depending upon whether the decomposition is accomplished by liquid air immersion or by tempering is believed to be the result of the mode of decomposition on the effectiveness of the five factors outlined previously. When austenite decomposes during tempering the stresses set up within the specimens by quenching are relieved. The decomposition proceeds in tempering more slowly, giving time for the precipitation of cementite and subsequent coalescence of the particles. During tempering the growth of ferrite particles also takes place as the temperature is increased. The decomposition of martensite and troostite accompanies the decomposition of austenite during tempering within the range, 977 degrees Fahr. (525 degrees Cent.) to 1121 degrees Fahr. (605 degrees Cent.). On the other hand, when the retained austenite decomposes during immersion in liquid air the quenching stresses are still present and the coalescence of cementite and growth of ferrite particles is impeded by the low temperature. The rate of decomposition of austenite is rapid during immersion in liquid air as indicated by the greater part of the total change taking place within the first eight hour period of immersion.

SUMMARY

From the present investigation of the effect of the decomposition of austenite retained in a 5 per cent tungsten steel on the change in

magnetic properties certain definite relationships have been established. These relationships, however, are not of such a character that they permit mathematical formulations between the amount of austenite present after any given heat treatment and the magnetic properties.

More austenite was retained in the specimens quenched from the higher temperatures as indicated, first, by the greater density change upon quenching; and, second, by the secondary hardness effect during tempering, in the bars quenched from 2000 degrees Fahr. (1097 degrees Cent.).

The bars quenched in oil showed a greater density than did the bars quenched in water or 5 per cent sodium hydroxide. Bars quenched in water from 1800 degrees Fahr. (983 degrees Cent.) or above showed a greater density than did the bars quenched in 5 per cent sodium hydroxide. On the other hand, bars quenched in 5 per cent sodium hydroxide from below 1800 degrees Fahr. gave a greater density than did the bars quenched in water.

Austenite retained in the quenched tungsten steel was found to decompose most readily upon tempering within the temperature range 977 degrees Fahr. (523 degrees Cent.) to 1121 degrees Fahr. (605 degrees Cent.). The changes in magnetic properties which occurred upon tempering within this temperature range are the result of the decomposition of austenite in the quenched steel.

An apparent relation exists between the product $Br \times Hc$ and the quenching temperature but only in the quenched condition.

A definite relationship between the quotient Br/Hc and the quenching temperature was found to exist only in the quenched condition. The Br/Hc value for oil-quenched bars is consistently lower than the value for the bars quenched in water or 5 per cent sodium hydroxide by an amount which tends to become a constant. The value Br/Hc , also, shows a remarkable tendency to become a constant. Oil quenching produces more retained austenite than either water or 5 per cent sodium hydroxide quenches. These two findings are in agreement with the results of previous investigators.

A 5.70 per cent tungsten steel, containing 0.60 per cent carbon, quenched in oil gave a lower value of maximum induction (B_m), residual (Br), product ($Br \times Hc$) and quotient (Br/Hc) than when quenched in water or 5 per cent sodium hydroxide. Oil-quenched specimens gave higher value of coercive force (Hc) and a greater

density for all quenching temperatures 1600 degrees Fahr. (871 degrees Cent.) to 2000 degrees Fahr. (1097 degrees Cent.), inclusive.

The greater change in density of the quenched tungsten steel bars upon immersion in liquid air was found to occur, first, when the quenching took place from the lower temperatures; and, second, when the quenching was carried out in oil.

The decomposition of the austenite by immersion in liquid air, while taking place largely within the first eight hours, was gradually increased with prolonged immersion.

The decomposition of austenite by immersion in liquid air was influenced by the quenching temperatures. Austenite retained in the bars quenched from the higher temperatures showed a greater degree of stability upon immersion in liquid air than did the austenite retained by quenching from the lower temperatures.

The effects of the decomposition of austenite in the quenched steel on the magnetic properties are summarized in the following outline, together with the changes in density and Rockwell C hardness.

Property	Decomposition of Austenite During	Decomposition of Austenite Upon Immersion in Liquid Air
Density	Drawing	decrease
Hardness	decrease	decrease
Maximum inductance Bm	increase	decrease
Residual inductance Br	decrease	increase
Coercive force Hc	increase	increase
Product Br x Hc	increase	decrease
Quotient Br/Hc	increase	increase
Maximum of permeability B/H	decrease	increase
Permeability B/H	decrease	increase
		

The observed differences in effect of austenite decomposition depending on whether the decomposition is effected by liquid air immersion or by tempering are believed to be the result of mode of decomposition on the effectiveness of certain factors in liquid air treatment which come into normal effectiveness during decomposition upon tempering. Decomposition during tempering follows the austenite-martensite-troostite-sorbite type of change while in liquid air the decomposition simulated the austenite-troostite change without the accompanying growth of cementite and ferrite particles.

BIBLIOGRAPHY

1. Dowdell, R. L., and Harder, O. E., "The Decomposition of the Austenitic Structure in Steel", *TRANSACTIONS, American Society for Steel Treating*, Vol. 11, 1927, p. 17-41.

2. Nusbaum, C., "Certain Aspects of Magnetic Analysis", *Proceedings, American Society for Testing Materials*, Vol. 19, part II, 1919, p. 96-116.
3. Mathews, J. A., "Retained Austenite; A Contribution to the Metallurgy of Magnetism", *TRANSACTIONS, American Society for Steel Treating*, Vol. 8, 1925, p. 565-583.
4. Dowdell, R. L., and Harder, O. E., "The Decomposition of the Austenitic Structure in Steels", part II, "The Decomposition of Austenite in Liquid Oxygen", *TRANSACTIONS, American Society for Steel Treating*, Vol. 11, 1927, p. 391-398.
5. Bain, E. C., and Waring, W. S. N., "Austenite Decomposition and Length Changes in Steel", *TRANSACTIONS, American Society for Steel Treating*, Vol. 15, 1929, p. 69-95.
6. Honda, K., and Iwase, K., "On the Transformation of Retained Austenite into Martensite by Stress", *TRANSACTIONS, American Society for Steel Treating*, Vol. 11, 1927, p. 399-412.
7. Honda, K., and Osawa, A., "On the Distribution of Austenite in Specimens of quenched Carbon Steels", *Science Reports, Tohoku Imperial University, Sendai, Japan*, Vol. 18, 1929, p. 47.
8. Tamman, G., and Scheil, E., "Die Umwandlungen des Austenit und Martensit in Gehärteten Stählen", *Zeitschrift für Anorganische und Allgemeine Chemie*, Vol. 157, 1927, p. 1-21.
9. Schroeter, K., "Über die Umwandlung des Austenit in Martensit durch flüssige Luft", *Zeitschrift für Anorganische und Allgemeine Chemie*, Leipzig, Vol. 169, 1928, p. 157-160.
10. Maurer, E., and Schroeter, K., "Die Bestimmung des Austenitgehaltes durch Messung des magnetischen Sättigungswertes und die Vorgänge beim Anlassen gehärteter Stähle", *Stahl und Eisen*, Vol. 49, 1929, p. 929-941.
11. Nurbury, A. L., "Volumes Occupied by the Solute Atoms in Certain Metallic Solid Solutions and their Consequent Hardening Effects", *Transactions, Faraday Society*, Vol. 19, 1924, p. 586.
12. Bain, E. C., "Secondary Hardness in Austenitized High Carbon-Chromium Steels", *TRANSACTIONS, American Society for Steel Treating*, Vol. 5, 1923, p. 89-101.

